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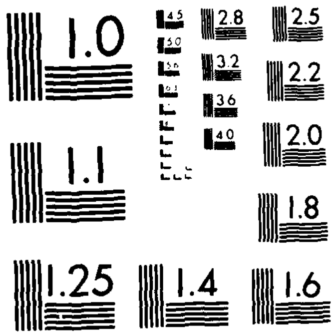

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THE POSITION AND MOBILITY OF THE SHOULDER, SPINAL COLUMN AND PELVIS IN SEATED SUBJECTS

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FEBRUARY 1985

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AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY
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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Air Force Aerospace Medical Research Laboratory

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This report describes the results and data formats for a study to investigate the three-dimensional internal kinematics of the human shoulder complex, individual vertebrae and the pelvis in unembalmed cadavers by means of stereoradiography. The motion is measured by tracking three-dimensional displacements of multiple radio opaque targets imbedded in the clavicle, scapula, sternum, humerus, a number of vertebrae, and the pelvis. The motion is produced by repositioning the cadavers to produce various degrees of spinal flexion and extension approximating different seated positions. To produce motion in the shoulder complex, the upper arm was moved in adduction and abduction. Sufficient targets were tracked on each of the motion segments to describe six-degree-of-freedom motion for each. In this study, data were collected on three cadavers and analyzed to provide descriptions of motion by position, vectors of targets imbedded with respect to anatomical landmarks and screw axis parameters both expressed with respect to an external fixed

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reference system and to the adjacent motion segment. A detailed description is provided of the data formats used in generating a magnetic tape, containing the analyzed experimental data, for the Air Force Aerospace Medical Research Laboratory.

PREFACE

Research reported herein was conducted under contract F33615-82-K-0516 with the Air Force Aerospace Medical Research Laboratory, U. S. Air Force, Wright-Patterson AFB, Ohio. This research investigation has been conducted in Systems Anthropometry Laboratory which has been constructed and supported by funds from the Air Force Office of Scientific Research, Air Force Aerospace Medical Research Laboratory, and the College of Osteopathic Medicine, Michigan State University. Principal investigator is Herbert M. Reynolds, Ph.D., Associate Professor, Department of Biomechanics, Department of Anthropology, Michigan State University. Mr. Charles E. Clauser, Workload and Ergonomics Branch, Wright-Patterson AFB acted as contract monitor; and Ints Kaleps, Ph.D., Chief, Modeling and Analysis Branch, Biodynamics and Bioengineering Division, Wright-Patterson, AFB acted as Senior Technical Advisor.

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1.0 INTRODUCTION

1.1 RESEARCH OVERVIEW.

Systems Anthropometry Laboratory (SAL) at Michigan State University conducts three-dimensional anthropometric investigations into the position and mobility of the human body. The experimental and analytical procedures in this investigation treat the human skeletal system as a system of rigid body links. A link in the human skeletal system consists of a bone separating two anatomical joints; and, on any bone, at least three anatomical pointmarks are defined, measured, and used to establish a three-dimensional frame of reference representing a rigid body. Therefore, the position of the skeletal link is specified with respect to an external inertial reference frame or an internal skeletal reference frame. With this analytical capability, joint kinematics are measured and described.

The purpose of collecting and analyzing three-dimensional anthropometric data is to improve the biofidelity of computer simulations of both the workspace (i. e., cockpit, VDU workspace, etc.) or dynamic response of the human body to acceleration or deceleration environments (i. e., pilot ejection, occupant protection, etc.). Three-dimensional anthropometric data that describe position and mobility of the human body are similar for both computer simulations. The goal of SAL's research is to provide more accurate data on the human torso, specifically, in our present program, the three-dimensional anthropometric and kinematic geometry of the torso from the hip to the shoulder joints.

1.2 DESCRIPTION OF FINAL REPORT CONTENTS

Research under AFAMRL Contract #F33615-82-K-0516 has investigated position and motion geometry of the spinal column and shoulder in three adult, male cadavers. The experimental and analytical protocols were described in a previous AFAMRL Final Technical Report (AFAMRL-TR-83-016). A similar experimental protocol has been used to obtain the data submitted on magnetic tape. This Final Report will briefly describe additions and changes to the protocol such as the measurement of shoulder abduction in the frontal (YZ) plane.

The purpose of this report is to describe the content and format of the data accompanying this report. These data are organized on two 9-track, 800 bpi, magnetic tapes into five files written in ASCII code in the following manner:

Tape I: File 1: Anatomical pointmark position vectors for all bones and body positions in the SRP frame of reference.

File 2: Transformation matrix for each bone in each posture-position from the SRP frame to the anatomical frame of reference of a bone.

File 3: Anatomical pointmark position vectors for all bones and body positions in the anatomical frame of reference of the adjacent, inferior bone.

Tape II: File 4: Parameters describing motion of individual bones relative to the seat (SRP frame of reference).

File 5: Parameters describing motion of an individual bone relative to an adjacent, inferior, bone (anatomical frame of reference, see Appendix C).

The following section on materials and methods summarizes the experimental procedures used to obtain these data. In the following section, an example of data from each file and an explanation or reference for each parameter is presented. Following each example, a complete set of documentation by card, field, column and item description is given.

2.0 METHODS AND MATERIALS

2.1 EXPERIMENTAL METHOD.

The Systems Anthropometry Laboratory has been developed to measure accurately in three-dimensional space the position and mobility of the human body (Reynolds, Hallgren, and Marcus, 1981). A stereoradiographic technique yields data describing sitting postures with the 3-D position vectors of anthropometric and anatomic pointmarks on the body surface and in the skeletal system. Motion parameters are calculated to describe the change of position of individual bones, that is the kinematics of the human linkage system, both with respect to an external body reference and to an internal reference in the adjacent, inferior bone.

Three to six tungsten-carbide balls are implanted in the following bones of the cadaver before the stereoradiographs are made:

Rt. Humerus	Rt. Scapula	Rt. Clavicle	Sternum
C7	T1	T4	T8
T12	L1	L2	L3
L4	L5	Sacrum	Rt. & Lt. Hip Bones

The following surface landmarks are targeted on Subject #23 with lead crosses:

Rt. Iliospinale	Lt. Iliospinale
Symphysion	Suprasternale
Rt. Acromion	Lt. Acromion

The subject is seated in a hard wooden seat representative of Air Force seat geometry. Stereoradiographs are made of each position representing the postures listed in Table 2.1.

POSTURES	NO. OF POSITIONS MEASURED		
		Subject	
	#21	#22	#23
Lumbar Extension	6	8	8
Lumbar Flexion	7	8	6
Rt. Shoulder Abduction	10	7	8
Rt. Lateral Sidebending	0	2	2
Lumbar-Knee Angle	0	0	3
Lumbar Support Height	4	0	0

Table 2.1 List of Postures and the number of measured positions for each subject.

Card	Field	Columns	Item Description
00	1	01-02	Card Number (00)
		03-04	Subject number (21)
		05	Posture Numeric Code
			0 = LBAREXT (Lumbar extension)
			1 = LBARFLEX (Lumbar flexion)
			2 = SIDEBDRT (Sidebending right)
			4 = SHABDUCT (Shoulder abduction)
			6 = LBARKNEE (Knee flexion tests)
			7 = LBARH (Lumbar support device)
		06	Position Number
			0 = Beginning position
			1 = Next position
			n = Sequential positions
		07-08	Bone Numeric Code (Appendix A)
			09 = Left Hip (LHIP)
			10 = Right Hip (RHIP)
			11 = Sacrum (SAC)
			14 = L05
			15 = L04
			16 = L03
			17 = L02
			18 = L01
			20 = T12
			24 = T08
			28 = T04
			31 = T01
			32 = C07
			39 = Sternum (STE)
			41 = Right Clavicle (RCLA)
			43 = Right Scapula (RSCA)
			45 = Right Humerus (RHUM)
		09-10	Anatomical Pointmark Numeric Code (See Appendix A for complete listing)
			01 = Right Transverse Process
			02 = etc.
	2	11-14	Reference Frame Name (Examples below, field 7-8 gives abbreviations)
			SRP- SRP axis system
			L05- Anatomical axis system for the fifth lumbar vertebra.
			LHIP Anatomical axis system for the left hip.
		15-20	"FRAME "
	3	21-28	Posture Name
			LBAREXTN
			LBARFLEX
			SIDEBDRT
			SHABDUCT
			LBARKNEE
			LBARH
		29-30	Same as columns 5 and 6
			00 = LBAREXTN beginning position

The alpha-numeric codes for posture, position, bone, anatomical pointmark will only be described in this section.

Rules regarding the data in File 1 are as follows:

1. If a bone does not exist for a posture-position sequence, there will be no data (that is, the missing data code is not used). However, if a bone is present for at least one position in a motion series, all missing pointmarks on the bone will be coded with a 999.99 for the other positions in the same posture-position sequence.

2. The unit of measure for all translational data is the centimeter—two places to the right of the decimal are used (±xx.xx).

3. Each field is composed of 10 columns (F10.2 or A10).

4. All alpha entries are left justified and all numeric entries are right justified.

Figure 4.1 gives an example of file 1. These data illustrate the first 18 lines of data in the file. They contain position vectors for the hip and sacrum of subject #21 in the LBAREXTN00 posture-position.

```
002100090OSRP-FRAME LBAREXTNOOHIPACELMMM      7.55      4.61     11.55L HIP
0021000911SRP-FRAME LBAREXTNOOHIPILILPSM     -1.11      2.89     15.97L HIP
002100093OSRP-FRAME LBAREXTNOOHIPISCLMIC      5.59      5.09      3.42L HIP
002100095OSRP-FRAME LBAREXTNOOHIPPUBLAMC     13.86      1.29     10.18L HIP
002100097OSRP-FRAME LBAREXTNOOHIPSIJLMML      3.12      4.15     17.29L HIP
002100100OSRP-FRAME LBAREXTNOOHIPACERMMM      7.03     -7.04     11.12R HIP
0021001011SRP-FRAME LBAREXTNOOHIPILIRPSM     -0.95     -5.46     16.21R HIP
002100103OSRP-FRAME LBAREXTNOOHIPISCRMIC      5.53     -6.11      3.17R HIP
002100105OSRP-FRAME LBAREXTNOOHIPPUBRAMC     14.00     -3.72      9.53R HIP
002100107OSRP-FRAME LBAREXTNOOHIPSIJRMML      3.53     -6.56     16.50R HIP
002100110OSRP-FRAME LBAREXTNOOSACSB1CASC      3.53     -1.29     20.17SACRUM
0021001101SRP-FRAME LBAREXTNOOSACSB1CPSC      5.68     -1.28     19.08SACRUM
0021001102SRP-FRAME LBAREXTNOOSACSB1RMSL      4.47     -3.39     19.86SACRUM
0021001103SRP-FRAME LBAREXTNOOSACSB1LMSL      4.43      0.81     13.65SACRUM
002100112OSRP-FRAME LBAREXTNOOSACSAPRMMC      1.86     -4.09     20.85SACRUM
002100113OSRP-FRAME LBAREXTNOOSACSAPLMMC      1.86      1.35     21.34SACRUM
002100114OSRP-FRAME LBAREXTNOOSACSIJRMML      3.40     -5.70     16.36SACRUM
002100116OSRP-FRAME LBAREXTNOOSACMC1CPMC     -0.31     -1.44     18.55SACRUM
```

Figure 4.1 Example of data in file 1.

File 1 documentation and tape format follow the figure. The data in this file have been sorted on numeric codes in the following sequence: subject number, posture, position, bone code and pointmark code.

4.0 TAPE FORMAT DESCRIPTION.

The two 9-track magnetic tapes have five files of data. The position vectors in the SRP and anatomical frames of reference as well as the parameters decribing body motions are presented in these files. These data have been written in each file for flexibility of data access. All data are written into 10-column fields (F10.2, F10.4, or A10), and both alpha and numeric codes for accessing the data are present. A complete set of rules for each file are given in each section describing the file.

4.1 TAPE I DOCUMENTATION.

Tape I has three files. File 1 contains all of the anatomical pointmark data for each bone in each posture-position of each subject in the SRP frame of reference. The origin of the SRP frame lies on the intersection of the seat pan surface and the seat back surface. The x-axis is positive in an anatomically anterior direction; the y-axis is positive in an anatomically left lateral direction (i.e., the y-axis lies on the intersection line of the seat pan and back surfaces); and the z-axis is positive in an anatomically superior direction (i.e., parallel to the gravity vector).

File 2 reports the 4 x 4 matrix for transforming the anatomical pointmark data for each bone in each posture-position from the SRP frame to the bone's anatomical frame.

File 3 reports all of the anatomical pointmark data for each bone in each posture-position of each subject in the anatomical frame of reference of the inferior bone. This anatomical frame of reference is defined with three anatomical pointmarks for each bone (Appendix C). The analytical definition of the anatomical frame of reference is discussed in AFAMRL-TR-83-016, pp 35-39.

4.1.1 <u>File 1: Anatomical Pointmark Position Vectors in SRP Frame of Reference</u>

Data in File 1 are the three-dimensional position vectors of anatomical pointmarks in the SRP frame of reference. The first four fields describe the anatomical pointmark and the next three fields contain the position vectors.

TABLE 3.1 Relative Movement in Local Motion Segments from LBAREXTN00 to LBAREXTN07 for Subject # 23.

Bone		Translation (cm)			Rotation (degrees)		
Moving	Fixed	$\hat{i}$	$\hat{j}$	$\hat{k}$	$\hat{j}$	$\hat{k}$	$\hat{i}$
R Hip	L Hip	-0.08	-0.09	-0.02	0.25	-1.33	-0.08
Sacrum	R Hip	0.07	-0.25	0.07	0.65	1.91	-0.93
Sacrum	L Hip	-0.40	-0.18	0.08	1.31	0.73	0.19
L5	Sacrum	0.12	0.20	0.08	1.30	0.33	2.16
L4	L5	0.00	0.07	-0.09	-1.04	-1.21	-0.12
L3	L4	-0.01	-0.08	0.04	-0.18	0.62	0.51
L2	L3	-0.01	0.06	-0.07	-2.49	0.27	0.94
L1	L2	0.14	-0.02	-0.01	-7.90	-0.25	-1.46
T12	L1	0.03	0.02	0.05	-6.94	0.28	-0.42
T8	T12	0.88	0.17	-0.07	-5.14	1.41	2.27
T4	T8	-0.25	0.06	0.01	1.88	-2.44	-0.25
T1	T4	-0.16	-0.13	0.03	3.64	0.60	-1.13
C7	T1	-0.09	0.07	-0.01	4.37	-0.93	-0.96
R Clavicle	T1	0.22	0.02	0.08	-1.18	-2.44	0.21
R Scapula	R Clavicle	0.14	-0.02	0.14	0.28	2.52	1.37

The clavicle and scapula are each depicted on the illustration with anatomical pointmarks representing joint surfaces, anthropometric landmarks or anatomical features.

Figure 3.1b shows the same data in the frontal plane. The dorsal spine and anterior endplate pointmarks have been omitted from the spinal column to keep the illustration simple. These wireframe images can be created for each posture and subject and visual comparisons are easily made between postures and subjects.

3.2 ANATOMICAL POINTMARKS FOR INVESTIGATIONS OF LOCAL JOINT MOTIONS

With anatomical pointmarks defined on each bone in a global axis system, transforming the data into local anatomical axes systems permits a closer more representative examination of the relative motion between two bones. For example, when the motion of L3 is examined in the anatomical frame of L4, the relative motion of L3 can be studied as if L4 is a fixed, immoveable body.

Movement within motion segments has been computed and representative results are presented in Table 3.1. In this table, fifteen motion segments have been typically analyzed in the lumbar flexion and lumbar extension motion series. Fewer motion segments are available for shoulder abduction motion analysis. These data are reported in local frames of reference defined in the anatomically inferior bone in the spinal column. As in the example below, L4 is used to define an axis system for describing the relative motions of L3. For a complete discussion of axis system definition, see AFAMRL-TR-83-016. The calculation of relative translations and rotations is presented in Appendix D. The screw axis motion parameters also have been calculated to describe local motions.

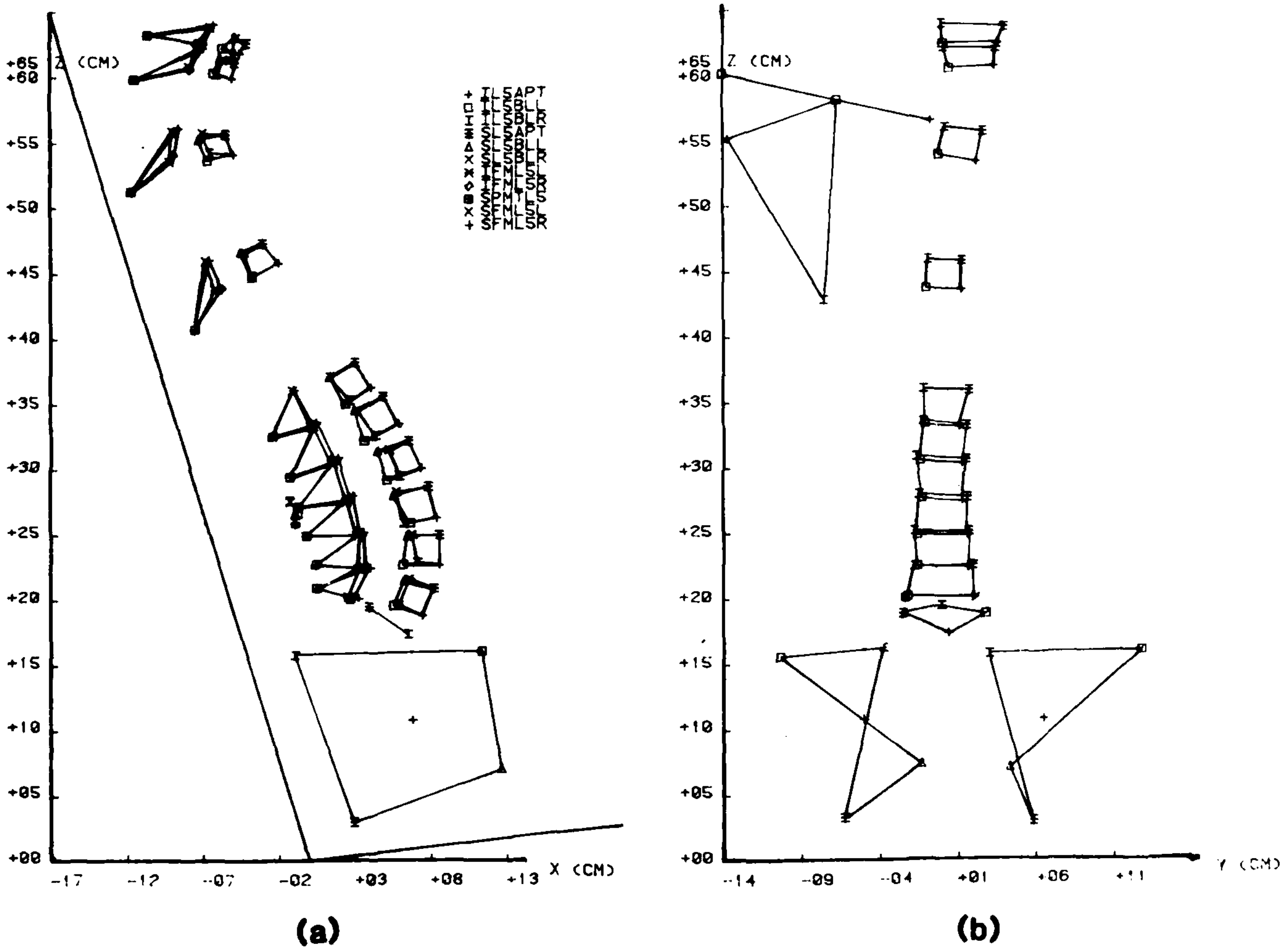


Figure 3.1 Wireframe images of spinal column in the sagittal plane (a) and frontal plane (b) for subject #23 in LBAREXTN07.

3.0 RESULTS

The data, measured on three subjects, form a unique description of seated skeletal geometry. Considerable effort has been expended to take measurements that describe the position and mobility of the shoulder, spinal column, and pelvis as a system. The experimental and analytical processes combine to supply data on skeletal positions in both global and local frames of reference (explained below). Additionally, these data are reported as position vectors defining anatomical pointmarks that are comparable between subjects. Thus, relative motions may be investigated in anatomical frames of reference that are comparable between subjects.

The following discussion provides examples of the data from this investigation. These examples serve primarily to illustrate the different types of data rather than portray the complete set of data.

3.1 ANATOMICAL POINTMARKS FOR INVESTIGATION OF BODY POSTURES IN A GLOBAL FRAME

Anatomical pointmarks are targeted and measured on 17 bones in the cadaver investigation. These data are transformed into the motion data frame so that their position is known as if it had been targeted throughout the investigation. More extensive discussion is available in AFAMRL-TR-83-016.

For a global examination of the complete torso--shoulder, spinal column and pelvis--position vectors are reported with respect to an external frame of reference defined in the Air Force seat. The origin of this axis system is at the seat reference point and the axes are parallel to the laboratory frame of reference. Each position vector defines an anatomical pointmark. In Figure 3.1a the wireframe image representing the skeleton in the sagittal plane are defined by connecting anatomical pointmarks on each bone. Each vertebra is represented by two polyhedra defining the vertebral body and dorsal spine.

The sacrum is seen at the base of the spine as a line connecting promontorion and a point on the posterior surface of the sacral base. The hip bones are represented by connecting four pointmarks on the anterior superior iliac spine, posterior superior iliac spine, ischial tuberosity, and pubic tubercle. The hip joint is marked by a cross inside the region defined by the four hip bone pointmarks.

side and tight hamstrings seem to restrict flexion in the left hip. Considerable muscle atrophy was observed in the right shoulder.

In the spinal column, tissues overlying the right sacroiliac joint felt firmer than over the left SI joint. The lower lumbar vertebrae (L3-5) appeared to resist rotation to the left. In the cervical region, the head moved greater in right sidebending and right rotation than to the opposite side.

In summary, subject #22 appeared to have more muscular asymmetry than positional and passive range of motion.

<u>Subject #23.</u>

There were no remarkable palpatory findings in the lower thoracic and lumbar region. In the cervical and upper thoracic region, a marked restriction to left rotation was observed.

There was a 1.5 cm difference in leg length (i.e. short left leg) which might correspond to the atrophied appearance of the right leg. In the passive flexion of the hip joint the right hamstrings were tighter than the left.

In summary, subject #23 had fewer clinical findings for joint dysfunction than in the other two subjects, but the physician noted more soft tissue observations than for the other subjects.

The cause of death for subject #21 was recorded as respiratory arrest due to brain tumor. Subject #22 was recorded as due to a metastatic carcinoma of the lung and Subject #23 was recorded due to a metastic carcinoma of the esphogus. In all three cases, the musculoskeletal system was in a reasonably healthy condition. An osteopathic physician examined each cadaver for any serious pathology in functional joint movements and passive soft tissue response. All three subjects had some dysfunction found in the palpatory examination, but they were not abnormally different from the types of musculoskeletal dysfunctions found in a typical out-patient clinical practice.

Each cadaver was examined in prone and supine positions by the same osteopathic physician. Rigor mortis had been broken prior to the exam by moving individual body segments through their anatomical ranges of motions. The following discussion summarizes the musculoskeletal examination findings.

Subject 21.

The musculoskeletal system had an overall symmetry in this subject. In the spinal column, asymmetries in the prominence of the transverse processes were palpated at T6-8 and L3-5. This asymmetry is interpreted by the physician to indicate a possible motion restriction between vertebral motion segments at these levels. Rotation of the head (i.e. chin to shoulder motion) appears to be less to the right than to the left. A motion restriction in the mid-cervical (C3-C4) region was palpated. There was also a mild scoliotic curvature with left convexity observed at T4-6.

In the pelvis, the left lumbosacral and sacroiliac joints seemed to have more motion restriction than the contralateral joints. The hip joints moved asymmetrically in internal rotation: left hip restricted and right hip hypermobile. There was some asymmetry in the position of the fibular head (right versus left legs) which may have been compensating for the hip joint asymmetries.

In summary, none of the findings would have been considered clinically significant. Treatment, manipulation and/or exercise, would probably change the asymmetrical joint function to symmetrical joint function. The size and shape of the musculoskeletal system was symmetrical in contrast to the relative asymmetrical joint functions.

Subject 22.

This subject had greater asymmetries of joint function in the extremeties than in the spinal column. In the hip, abduction is restricted on the right

determine if there had been any significant deterioration in these tissues. None was observed. In the other subjects, the normal protocol was followed. Targets were implanted immediately, anthropometric measurements were made, stereoradiographs were made, and the shoulder and spinal column were excised. The complete procedure was completed within 72 hours of death. In all cases, the anatomical pointmarks were identified before completely cleaning the bones; soft tissue was removed sufficiently to identify the anatomical structure and a target was implanted. In the case of the 33 year old subject, there are several pointmarks missing which we were unable to re-measure because the skeleton was not retained by SAL. The skeletal parts of the other two cadavers have been kept as part of the skeletal collection maintained by SAL for further study of osteological variation as it relates to spinal and shoulder kinematics.

The anthropometric description of body size (body weight and stature), torso length (Suprasternale to Symphysion), arm length (Acromion to Stylion), leg lengths (Trochanterion to lateral femoral epicondyle; Tibiale to Sphyrion), and seated shoulder height (Acromion height above SRP) are presented in Table 2.4. The measurements are made with the body lying supine on a flat surface, except seated shoulder height which was measured when the cadaver was seated for the lumbar motion investigation. The measurement of body weight is made by suspending the body from a scale. The three cadavers were similar in body proportion and of normal body build for their age and size.

Variable	Data		
Subject ID	#21	#22	#23
Age (yrs)	33	59	56
Weight (kg)	61.55	67.35	65.4
Stature (cm)	173.5	183.3	176.8
Torso Length	52.0	57.1	52.6
Rt. Arm Length	53.4	59.8	58.7
Rt. Femur Length	*	45.8	48.5
Rt. Tibia Length	*	39.3	41.2
Seated Shoulder Hgt.	59.3	61.5	55.6

Table 2.4 Anthropometry of cadaveric subjects.
(*These measurements were not made on subject #21.)

The turnbuckle axis represents the line of force acting on the arm. At the initial 30° shoulder abduction position, the line of force forms an approximately 120° angle to the long axis of the arm. As the arm approaches horizontal, the angle of the line of action to the arm axis decreases to approximately 90° and remains approximately tangential to the motion for the remainder of the arm abduction position series.

The motion of the shoulder linkage system with respect to the torso has been measured relative to the first thoracic vertebra (T1). The relative motions between T1, T4, T8, and T12 can be investigated to determine if these bones can be used to define a stable axis system for the thorax. Consequently, the motion of the clavicle, scapula and humerus could be studied relative to an axis system defined for the thorax by using three targets on three bones such as T1, T12 and the sternum.

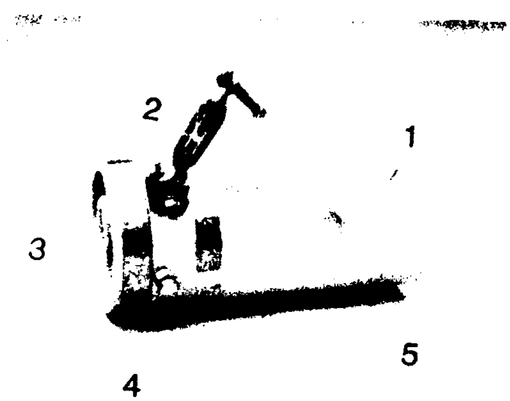
In every subject, more than the minimum 6 positions were measured. These additional positions represent either initial positions or additional translatory movements in the final position. For Subject #21, a series of body positions have been measured to represent changes in lumbar extension as a result of moving the support device to different vertical locations on the seat back. There are a total of four vertical heights from the seat pan at which the support bar was located. The LBAREXTN position series are measured at one height position and there are three additional height positions of the support bar: one below and two above the position series location.

For Subject #23, a series of body positions also representing changes in the amount of knee flexion have been measured. The first position is similar to the first position in all the other motion series. The second and third positions represent additional flexion of the knee with the torso position changing only in response to the knee position.

2.2 EXPERIMENTAL MATERIALS.

Three unembalmed male cadavers have been measured. The ages of these three cadavers are 33, 59, and 56. The normal experimental procedure is to take all measurements on the body within 72 hours after death. The 33 year old subject was held in a cooler at 35° C for 18 days before being measured. Equipment failure delayed the experiment. Upon completion of the measurements of this cadaver, samples of muscle and tendon were examined histologically to

attachments to trolley and arm cuff so that it rotates about two parallel axes that are perpendicular to the plane of motion. Each arm cuff is rigidly attached to the arm with a Steinman pin through the cuff and humerus. Two adjustable curved surfaces inside the cuff clamp the forearm to prevent axial rotation (Figure 2.1). Right and left arms are moved symmetrically through a frontal plane taking stereoradiographic measurements at 30°, 60°, 90°, 120°, 150°, and 180° positions where 0° is defined by the arm hanging at the side of the body. These positions were defined trigonometrically by arm length (shoulder joint to radial stylion) and the heights from the floor of radial stylion and the shoulder joint.



1 Steinman Pin
2 Turnbuckle
3 Adjustable forearm clamp
4 Wrist end
5 Shoulder end

Fig. 2.1 Arm Cuff to Control the Arm Move as a Rigid Body.

Lumbar flexion positions in the seated subject are produced by moving the pelvis anteriorly from the seat back. The cadaver's legs are pulled forward in small increments represented by ISCHIALE (HIPISCRIMIC, 1030). The position vectors for left ISCHIALE are reported in Table 2.3. The average distances between consecutive flexion positions of left ISCHIALE are 2.02 cm (#21), 2.29 cm (#22), and 2.32 (#23).

	#21			#22			#23		
LBARFLEX	X	Y	Z	X	Y	Z	X	Y	Z
10	5.59	5.09	3.42	6.18	6.16	2.21	4.21	5.66	2.67
11	8.46	4.76	3.39	9.59	5.76	2.51	5.65	5.40	2.33
12	10.75	4.67	3.85	12.85	5.61	2.95	8.82	5.48	2.72
13	12.71	4.18	3.87	14.71	5.58	3.22	10.72	5.38	2.46
14	14.45	4.10	3.76	16.36	5.44	3.53	13.70	5.22	2.59
15	16.07	3.79	3.88	18.78	5.10	4.01	15.67	5.17	2.95
16	17.59	3.63	4.03	20.30	4.81	4.28	—	—	—
17	—	—	—	21.91	4.62	4.58	—	—	—

TABLE 2.3 Position vectors (SRP frame) of Left Ischiale in the LBARFLEX motion series by subject number.

Shoulder abduction motions have been measured for the first time in SAL. The shoulder linkage system is composed of four bones: sternum, clavicle, scapula, and humerus. These four bones and their joints (gleno-humeral, acromio-clavicular, scapulo-thoracic, and sterno-clavicular) provide the motion capability of the shoulder linkage system. A kinematic system has been designed to limit motion of the shoulder to a frontal plane. The arm is attached to a mechanical linkage composed of a metal track and two trolleys on each side of the body which up and over an arch above the head of the subject. The trolleys (moving in the laboratory YZ plane) are initially pulled along the track in a vertical direction until the arm is approximately horizontal at which position, the track begins to curve with a 19-inch radius. The arm is attached to the trolley with a turnbuckle which forms a fixed length link joining the trolley and the arm cuff. The turnbuckle is designed at the

After all stereoradiographs have been made, the targeted bones are excised and additional targets are implanted at specific anatomical pointmarks on the bones. Definitions of all pointmarks used in this study are in Appendix A. Another set of stereoradiographs is made of these individual bones with cadaver and anatomical pointmark targets in place so that a transformation can be calculated between them and the motion of the segment with respect to the anatomical pointmarks (See AFAMRL-TR-83-016 for calculation details). All films are digitized and the three-dimensional Cartesian coordinates are calculated. These data, stored in the computer, are used in the analysis of relative motions.

The experimental design used to investigate lumbar extension, lumbar flexion, and lateral sidebending motions has been described in AFAMRL-TR-83-016. Lumbar extension positions in the seated subject are established with a hemi-cylindrical bar, length = 60.3 cm and radius = 1.85 cm. Six 0.8 cm tungsten carbide balls have been implanted in the bar and are measured at each body position. One target has been selected to represent the displacement of the bar relative to the seat back. The location of the bar in the lumbar extension motion series for all subjects is described by position vectors in Table 2.2. The average distances between consecutive positions of this target are 0.61 cm (#21), 0.66 cm (#22), and 0.58 cm (#23).

	#21		#22		#23	
LUMBAREXTN	X	Z	X	Z	X	Z
01	-4.12	25.97	-4.38	26.06	-4.24	26.12
02	-3.02	26.12	-3.86	26.26	-3.55	26.27
03	-2.42	26.22	-3.14	26.36	-2.94	26.23
04	-2.30	26.30	-1.68	26.14	-2.36	26.35
05	-1.72	26.39	-1.54	26.48	-1.84	26.48
06	---	---	-1.27	26.65	-1.22	26.58
07	---	---	-0.88	26.86	-0.86	26.72

TABLE 2.2 Position vectors (SRP frame) of lumbar support device in LBAREXTN motion series by subject number.

		01 = LBAREXTN first position 0n = LBAREXTN next position 09 = LBAREXTN maximum last position
4	31-33	Bone Alpha Abbreviation (Appendix A)
	34-36	Structure Name (Appendix A)
	37	Anatomical Pointmark Location Code (Appendix A) L = left of mid-sagittal plane R = right of mid-sagittal plane C = in the mid-sagittal plane
	38	Anatomical Pointmark Location Code (Appendix A) A = anterior P = posterior M = in between anterior & posterior
	39	Anatomical Pointmark Location Code (Appendix A) S = superior I = inferior M = in between superior & inferior
	40	Anatomical Pointmark Location Code (Appendix A) L = lateral M = medial C = in between lateral & medial
5	41-50	Anatomical Pointmark X-Coordinate in SRP Frame
6	51-60	Anatomical Pointmark Y-coordinate in SRP Frame
7	61-70	Anatomical Pointmark Z-coordinate in SRP Frame
8	71-80	Bone Name CERVICAL07 THORACIC01 LUMBAR 01 SACRUM R HIP L HIP STERNUM R CLAVICLE R SCAPULA R HUMERUS

4.1.2 File 2: Transformation Matrices from SRP to Anatomical Frames of Reference

File 2 contains the transformation matrix for each bone from the SRP frame to the anatomical frame of the bone. The anatomical frame is analytically defined in AFAMRL-TR-83-016 but the pointmarks and axes directions are given in Appendix C of this report. The first two fields of each card document the bone in numeric (field 1) and alpha (field 2) codes.

Rules regarding the data in File 2 are as follows:

1. If a bone does not exist for a posture-position sequence, there will be no data (that is, the missing data code is not used).
2. All elements of the matrix are presented with 4 places to the right of the decimal (.xxxx).
3. Each field is composed of 10 columns (F10.4 or A10).
4. All alpha entries are left justified and all numeric entries are right justified.

Figure 4.2 gives an example of the data in file 2. This example contains the first eighteen lines of data in the file for the transformation matrix from the SRP to the anatomical frame for the left and right hips, sacrum, L05, L04, and L03 of subject #21.

00210009	LBAREXTNOOL HIP		0.9282	-0.0989	-0.3588	-3.4541	0.2064
01210009	0.9390	0.2752	-6.8 58	0.3096	-0.3295	0.8919	-12.9455
02210009	0.0000	0.0000	0.0000	1.0000			
00210010	LBAREXTNOOR HIP		0.9079	0.1055	-0.4056	-3.0929	-0.1735
01210010	0.9756	-0.1347	7.3476	0.3815	0.1927	0.9040	-13.2405
02210010	0.0000	0.0000	0.0000	1.0000			
00210011	LBAREXTNOOSACRUM		-0.9126	0.0134	0.4086	-3.9943	-0.0076
01210011	0.9987	-0.0497	2.3163	-0.4088	-0.0485	-0.9114	19.7615
02210011	0.0000	0.0000	0.0000	1.0000			
00210014	LBAREXTNOOLUMBAR 05		0.9928	0.1148	-0.0356	-3.2561	-0.1123
01210014	0.9923	0.0512	0.7374	0.0412	-0.0469	0.9981	-21.0809
02210014	0.0000	0.0000	0.0000	1.0000			
00210015	LBAREXTNOOLUMBAR 04		0.9146	0.0171	0.4039	-13.3376	-0.0541
01210015	0.9953	0.0803	-0.4597	-0.4006	-0.0953	0.9113	-20.9542
02210015	0.0000	0.0000	0.0000	1.0000			
00210016	LBAREXTNOOLUMBAR 03		0.8850	0.0419	0.4638	-14.3181	-0.0577
01210016	0.9981	0.0201	1.0995	-0.4621	-0.0445	0.8857	-23.8834
02210016	0.0000	0.0000	0.0000	1.0000			

Figure 4.2 Example of data in file 2.

File 2 documentation and tape format are presented below. The data in this file have been sorted on numeric codes in the following sequence: subject, posture, position and bone.

Card	Field	Columns	Item Description
00	1	01-02	Card Number
		03-04	Subject Number
		05	Posture Numeric Code
		06	Position Number
		07-08	Bone Numeric Code
		09-10	Blank
	2	11-18	Posture Name
		19-20	Same as columns 5 and 6
	3	21-30	Bone Name
	4	31-40	Transformation Matrix (1,1)
	5	41-50	TM (1,2)
	6	51-60	TM (1,3)
	7	61-70	TM (1,4)
	8	71-80	TM (2,1)
01	1	01-10	Same as Card 00
	2	11-20	TM (2,2)
	3	21-30	TM (2,3)
	4	31-40	TM (2,4)
	5	41-50	TM (3,1)
	6	51-60	TM (3,2)
	7	61-70	TM (3,3)
	8	71-80	TM (3,4)
02	1	01-10	Same as Card 00
	2	11-20	TM (4,1)
	3	21-30	TM (4,2)
	4	31-40	TM (4,3)
	5	41-50	TM (4,4)

4.1.3 File 3: Anatomical Pointmark Position Vectors in Anatomical Frames of Reference

The documentation and tape format for File 3 is the same as for File 1 except that the cartesian coordinate data are presented in the anatomical frame of reference of the preceding bone (in anatomical terms, this is the inferior bone).

Rules regarding the data in File 3 are as follows:

1. If a bone does not exist for a posture-position sequence, there will be no data (that is, the missing data code is not used).

2. The unit of measure for all translational data is the centimeter—two places to the right of the decimal are used ($\pm$xx.xx).

3. Each field is composed of 10 columns (F10.2 or A10).

4. All alpha entries are left justified and all numeric entries are right justified.

Figure 4.3 gives an example of the data in file 3. This example contains the first eighteen lines of anatomical pointmark coordinate data for the hip,

sacrum and L05 of subject #21. This file has been sorted on numeric codes in the following sequence: subject number, posture, position, bone code and pointmark code.

```
0021001000LHIPFRAME LBAREXTNOOHIPACERMMM     -.22     -8.98      1.47R HIP
0021001011LHIPFRAME LBAREXTNOOHIPILIRPSM    -9.61     -7.74      3.02R HIP
0021001030LHIPFRAME LBAREXTNOOHIPISCRMIC     1.15    -10.60     -6.39R HIP
0021001050LHIPFRAME LBAREXTNOOHIPPUBRAMC     6.49     -4.86      1.12R HIP
0021001070LHIPFRAME LBAREXTNOOHIPSIJRMML    -5.45     -7.77      5.03R HIP
0021001100RHIPFRAME LBAREXTNOOSACSB1CASC    -8.20      2.76      6.09SACRUM
0021001101RHIPFRAME LBAREXTNOOSACSB1CPSC    -5.81      2.55      5.93SACRUM
0021001102RHIPFRAME LBAREXTNOOSACSB1RMSL    -7.45       .59      5.76SACRUM
0021001103RHIPFRAME LBAREXTNOOSACSB1LMSL    -6.95      4.72      6.37SACRUM
0021001120RHIPFRAME LBAREXTNOOSACSAPRMMC   -10.30       .22      5.53SACRUM
0021001130RHIPFRAME LBAREXTNOOSACSAPLMMC    -9.92      5.47      7.02SACRUM
0021001140RHIPFRAME LBAREXTNOOSACSIJRMML    -7.25     -1.00      1.75SACRUM
0021001160RHIPFRAME LBAREXTNOOSACMC1CPMC   -11.05      3.49      3.13SACRUM
0021001400SAC-FRAME LBAREXTNOOL05BODCASC     -.04      -.04     -4.00LUMBAR  05
0021001402SAC-FRAME LBAREXTNOOL05BODRMSL     1.26     -2.69     -3.09LUMBAR  05
0021001403SAC-FRAME LBAREXTNOOL05BODLMSL     1.78      2.28     -3.37LUMBAR  05
0021001407SAC-FRAME LBAREXTNOOL05BODCAIC    -1.03       .11     -1.64LUMBAR  05
0021001409SAC-FRAME LBAREXTNOOL05BODRMIL      .39     -2.38      -.81LUMBAR  05
```

Figure 4.3 Example of data in file 3.

4.2 Tape II Documentation and Tape Format.

Tape II has two files. File 4 contains all of the relative motion parameters describing the movement of each bone with respect to the seat. Thus the moving body is the bone and the fixed body is the seat, defined by the SRP axis system. The relative motion parameters consist of displacement matrix, the translation and rotation along and about the screw axis, the direction cosines for the screw axis with respect to the fixed axis system, the three piercing points, the position vector of the point on the screw axis closest to the origin of the fixed body reference frame, the origin of the moving body axis system in the first and second positions, the translation of the origin and the relative rotations of the moving body about each of the axes of the fixed body reference frame. The analytical definition of the relative motion parameters is discussed in AFAMRL-TR-83-016, pp 45-61. The discussion of the translation of the origin and the relative rotations of the moving body about each of the axes of the fixed body reference frame is in Appendix D of this report.

File 5 contains the same parameters describing motion with respect to the anatomical axis system of the below bone. That is, the motion of each bone is calculated relative to the anatomically inferior bone.

4.2.1 File 4: Bone-to-Seat Motions

The parameters describing the relative motion of each bone to the Seat, (SRP frame of reference) are given in file 4. The documentation of moving body, fixed body, and posture-positions is given in fields 1 and 2 of each card in file 4. Alpha-numeric codes are given for this information.

Rules regarding the data in file 4 are as follows:

1. If a bone does not exist for a posture-position sequence, there will be no data (that is, the missing data code is not used).

2. The unit of measure for all translational data is the centimeter--two places to the right of the decimal are used (±xx.xx). The unit of measure for all rotational data is degree--two places to the right of the decimal are used (.xx). Direction cosines, however, are reported with four places to the right of the decimal (.xxxx). All matrix data are presented with 4 places to the right of the decimal (.xxxx).

3. Each field is composed of 10 columns (F10.2, F10.4, or A10).

4. All alpha entries are left justified and all numeric entries are right justified.

Figure 4.4 gives an example of the data in file 4. This example contains the first eighteen lines of data in the file for subject #21. These data are the first set of motion data for the left hip moving relative to the seat and the right hip moving relative to the seat.

0021	00019109	LBAREXTNOOLBAREXTNO1SEAT			L HIP	0.9831	-0.0092
0121	00019109	0.1826	-1.9304	0.0105	0.9999	-0.0059	0.0500
0221	00019109	-0.1825	0.0077	0.9832	1.2305	0.0000	0.0000
0321	00019109	0.0000	1.0000	0.04	10.54	0.0373	0.9979
0421	00019109	0.0539	0.00	999.99	999.99	5.70	0.00
0521	00019109	11.11	999.99	999.99	0.00	5.67	-0.81
0621	00019109	11.06	8.63	1.85	12.20	8.78	1.90
0721	00019109	11.66	-0.15	-0.05	0.54	10.52	0.53
0821	00019109	0.44					
0021	00019110	LBAREXTNOOLBAREXTNO1SEAT			R HIP	0.9830	-0.0032
0121	00019110	0.1835	-1.9490	0.0047	1.0000	-0.0075	0.0945
0221	00019110	-0.1835	0.0082	0.9830	1.2988	0.0000	0.0000
0321	00019110	0.0000	1.0000	0.04	10.58	0.0428	0.9989
0421	00019110	0.0214	0.00	999.99	999.99	6.04	0.00
0521	00019110	11.19	999.99	999.99	0.00	6.02	-0.50
0621	00019110	11.18	9.13	-4.29	11.71	9.21	-4.26
0721	00019110	11.08	-0.08	-0.03	0.62	10.58	0.19
0821	00019110	0.47					

Figure 4.4 Example of data in file 4.

File 4 documentation and tape format follow the figure. The data in the file have been sorted on numeric codes in the following sequence: subject, 1st position of posture, 2nd position of posture, and moving body.

Card	Field	Columns	Item Description
00	1	01-02	Card Number
		03-04	Subject Number
		05-10	Blank
	2	11	Posture Numeric Code, 1st Position
		12	Position Number, 1st Position
		13	Posture Numeric Code, 2nd Position
		14	Position Number, 2nd Position
		15-16	Fixed Body Numeric Code (SEAT = 91)
		17-18	Moving Body: Bone Numeric Code
		19-20	Blank
	3	21-28	First Posture-Position Name
		29-30	Same as columns 11-12
	4	31-38	Second Posture-Position Name
		39-40	Same as columns 13-14
	5	41-50	Fixed Body Name
	6	51-60	Moving Body: Bone Name
	7	61-70	Displacement Matrix (1,1)
	8	71-80	DM (1,2)
01	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	DM (1,3)
	4	31-40	DM (1,4)
	5	41-50	DM (2,1)
	6	51-60	DM (2,2)
	7	61-70	DM (2,3)
	8	71-80	DM (2,4)

02	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	DM (3,1)
	4	31-40	DM (3,2)
	5	41-50	DM (3,3)
	6	51-60	DM (3,4)
	7	61-70	DM (4,1)
	8	71-80	DM (4,2)
03	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	DM (4,3)
	4	31-40	DM (4,4)
	5	41-50	Displacement on screw axis
	6	51-60	Rotation about screw axis
	7	61-70	Direction cosine about x-axis of fixed bone axis system
	8	71-80	Direction cosine about y-axis of fixed bone axis system
04	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	Direction cosine about z-axis of fixed bone axis system
	4	31-40	Piercing Point (x component) in the YZ plane
	5	41-50	PP (y component) in the YZ plane
	6	51-60	PP (z component) in the YZ plane
	7	61-70	PP (x component) in the XZ plane
	8	71-80	PP (y component) in the XZ plane
05	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	PP (z component) in the XZ plane
	4	31-40	PP (x component) in the XY plane
	5	41-50	PP (y component) in the XY plane
	6	51-60	PP (z component) in the XY plane
	7	61-70	X-coordinate of closest point on the screw axis to the reference frame origin
	8	71-80	Y-coordinate of closest point on the screw axis to the reference frame origin
06	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	Z-coordinate of closest point on the screw axis to the reference frame origin
	4	31-40	X-coordinate of origin of above bone axis system in the first position in the anatomical reference frame of below bone (SEAT-file 4)
	5	41-50	Y-coordinate of origin of above bone axis system in the first position in the anatomical reference frame of below bone (SEAT-file 4)

	6	51-60	Z-coordinate of origin of above bone axis system in the first position in the anatomical reference frame of below bone (SEAT-file 4)
	7	61-70	X-Coordinate of origin of above bone axis system in the second position in the anatomical reference frame of below bone (SEAT-file 4)
	8	71-80	Y-Coordinate of origin of above bone axis system in the second position in the anatomical reference frame of below bone (SEAT-file 4)
07	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	Z-Coordinate of origin of above bone axis system in the second position in the anatomical reference frame of below bone (SEAT-file 4)
	4	31-40	X-axis translation of the moving bone origin
	5	41-50	Y-axis translation of the moving bone origin
	6	51-60	Z-axis translation of the moving bone origin
	7	61-70	Angular displacement of moving body around the primary axis of rotation in the fixed body (Appendix D).
	8	71-80	Angular displacement of moving body around the secondary axis of rotation in the fixed body (Appendix D).
08	1	01-10	Same as Card 00
	2	11-20	Same as Card 00
	3	21-30	Angular displacement of moving body around the tertiary axis of rotation in the fixed body (Appendix D).

4.2.2 File 5: Bone-to-Bone Motions.

The relative motion parameters describing the movement of the anatomically functional segment (sometimes referred to as motion segments) are given in file 5. The data are formatted the same as in file 4 except that the motion parameters are calculated in an anatomical frame of reference.

The functional segments are given in Table 3. Each row describes a motion segment with the fixed body defining the axis system within which the motion of the moving body is described. The sequence in Table 3 is the same as in file 5.

Fixed Body	Moving Body
Left Hip	Right Hip
Right Hip	Sacrum
Sacrum	L05
L05	L04
L04	L03
L03	L02
L02	L01
L01	T12
T12	T08
T08	T04
T04	T01
T01	Sternum
Sternum	Clavicle
Clavicle	Scapula
Scapula	Humerus
Left Hip	Sacrum
T01	C07

Table 4.1 List of relative bone-to-bone motions analyzed in the linkage system of the body.

Rules regarding the data in file 5 are as follows:

1. If a bone does not exist for a posture-position sequence, there will be no data (that is, the missing data code is not used).

2. The unit of measure for all translational data is the centimeter—two places to the right of the decimal are used ($\pm$xx.xx). The unit of measure for all rotational data is degree—two places to the right of the decimal are used ($\pm$xx.xx). Direction cosines, however, are reported with four places to the right of the decimal (.xxxx). All matrix data are presented with 4 places to the right of the decimal (.xxxx).

3. Each field is composed of 10 columns (F10.2, F10.4, or A10).

4. All alpha entries are left justified and all numeric entries are right justified.

Figure 4.5 gives an example of the data in file 5. This example contains the first eighteen lines of data on subject #21. There are two sets of data in this example describing the motion first of the right hip and then the sacrum relative to the left hip in the anatomical frame of the left hip.

0021	00010910	LBAREXTNOOLBAREXTNO1L	HIP	R HIP		1.0000	0.0050
0121	00010910	-0.0004	-0.0266	-0.0050	1.0000	-0.0035	-0.0089
0221	00010910	0.0004	0.0035	1.0000	0.0576	0.0000	0.0000
0321	00010910	0.0000	1.0000	0.02	0.35	1.0000	1.0000
0421	00010910	1.0000	0.00	38.78	-58.21	999.99	0.00
0521	00010910	999.99	999.99	999.99	0.00	-1.82	-1.79
0621	00010910	-1.12	1.25	-5.80	1.74	1.19	-5.82
0721	00010910	1.77	0.06	0.02	-0.04	-0.02	-0.29
0821	00010910	0.20					
0021	00010911	LBAREXTNOOLBAREXTNO1L	HIP	SACRUM		1.0000	0.0036
0121	00010911	-0.0019	-0.0470	-0.0036	1.0000	-0.0002	-0.0427
0221	00010911	0.0019	0.0002	1.0000	0.0435	0.0000	0.0000
0321	00010911	0.0000	1.0000	-0.05	0.23	1.0000	1.0000
0421	00010911	1.0000	0.00	-113.32	-251.88	999.99	0.00
0521	00010911	999.99	999.99	999.99	0.00	-14.02	9.45
0621	00010911	-5.82	-6.28	-1.74	6.48	-6.35	-1.76
0721	00010911	6.51	0.07	0.02	-0.03	-0.11	-0.21
0821	00010911	0.00					

Figure 4.5 Example of data in file 5.

File 5 documentation and formats are the same as in file 4. The data in this file have been sorted by numeric code in the following sequence: subject number, 1st position of posture, 2nd position of posture, fixed body and moving body.

5.0 SUMMARY AND CONCLUSIONS.

This final report documents two tapes of data from Systems Anthropometry Laboratory containing the first complete description of spinal and shoulder motions in anatomical pointmark axes systems. These three subjects will form part of a large databank supplied to AFAMRL for improving the current simulations of the human body in static and dynamic environments.

The data describe sitting postures in a wooden seat that simulates an Air Force seat design. There are as many as 25 different body positions measured on each cadaver subject. The measured seated postures have been produced by changes in lumbar extension, lumbar flexion and sidebending. In addition to the description of changes in spinal posture, there is also an investigation of shoulder abduction. These descriptions are unique because the shoulder, spinal column, and pelvis are represented by position vectors describing the location of anatomical pointmarks. Consequently, the geometrical and mechanical properties of the human torso can be investigated relative to skeletal anatomy.

In conclusion, this work is unique to Systems Anthropometry. Additional research will continue to measure a larger sample with which statistical inferences can be drawn regarding mechanical hypotheses of hip, spinal, and shoulder kinematics.

6.0 APPENDICES

6.1 APPENDIX A: GLOSSARY OF ANATOMIC POINTMARKS

The following list of terms specify anatomical landmarks which are identified by the Systems Anthropometry Labaortory on the pelvis, spinal column and shoulder skeletal systems. The pointmark acronym by each pointmark is used in tape I, files 1 and 3, card 1, field 4, and the pointmark numeric code is used in tape I, files 1 and 3, card 1, field 1, columns 7-10.

The pointmark acronym is always composed of 10 letters. The first three letters are the bone name abbreviation followed by a three-letter description of the anatomical structure. The last four letters describe the position of the pointmark on the bone and structure. The definitions of these alpha codes are given in the documentation of file 1.

The pointmark numeric code is always a four digit number. The first two digits are the bone code and the last two digits are the pointmark code. These codes are given in the documentation of file 1.

SACRUM

POINTMARK ACRONYM	Code	POINTMARK DEFINITION
SACBD1CASC	1100	Promontorion: The midpoint of the anterior-superior margin on the base of the first sacral segment (excluding exostoses).
SACBD1CPSC	1101	Posterior Point on First Sacral Vertebral Body: The midpoint of the postero-superior margin on the base of the first sacral segment. This point is posterior to Promontorion.
SACBD1LMSL	1103	Left Lateral Point on First Sacral Vertebral Body: The most lateral point on the left articular surface of the first sacral body. In cases with "lipping" present, the point was estimated as the most lateral point on the superior surface that would be found in the general contour without any lipping.
SACBD1RMSL	1102	Right Lateral Point on First Sacral Vertebral Body: Same as description above, except on the right articular surface.
SACMC1CPMC	1160	Median Sacral Crest: The point is at the midpoint of the most superior posterior medial crest of the sacrum.
SACSIJLMML	1150	Sacroiliac Midpoint, Left Sacrum: The point that lies at the intersect of the lines which bisect the superior and inferior poles of the left sacroiliac joint.
SACSIJRMML	1140	Sacroiliac Midpoint, Right Sacrum: The point that lies at the intersect of the lines which bisect the superior and inferior poles of the sacroiliac.
SACSAPLMMC	1130	Superior Articular Facet, Midpoint, Left: The midpoint of the left articular facet of the sacrum.
SACSAPRMMC	1120	Superior Articular Facet, Midpoint, Right: The midpoint of the right articular facet of the sacrum.

VERTEBRAE

The fifth lumbar vertebra (L05) is used as an example. The complete list of vertebrae and their numeric code are given in the documentation for file 1, fields 7-8.

POINTMARK ACRONYM	Code	POINTMARK DEFINITION
L05BODCASC	1400	Superior Body Surface L05, Anterior Point: The midpoint of anterior-superior margin of the L05 superior body surface.
L05BODLMIL	1401	Superior Body Surface L05, Lateral Point Left: The most lateral point on the left side of the articular surface on the L05 superior body surface. In cases with "lipping" present, the point was estimated as the most lateral point on the superior surface that would be found in the general contour with no lipping present.
L05BODRMSL	1402	Superior Body Surface L5, Lateral Point Right: Same as description above, except on the right side of the articular surface.
L05BODCAIC	1407	Inferior Body Surface L05, Anterior Point: The midpoint of the anterior margin of the L05 inferior body surface.
L05BODLMIL	1410	Inferior Body Surface L05, Lateral Point Left: The most lateral point on the left side of the articular surface of the L05 superior body surface.
L05BODRMIL	1409	Inferior Body Surface L05, Lateral Point Right: Same as left.
L05TRPLMML	1485	Transverse Process L05, Left Side: The most projecting point on the left transverse process of L05. In the case of a large contact area, the midpoint of the contact area is targeted.
L05TRPRMML	1480	Transverse Process L05, Right Side: The most projecting point on the right transverse process of L05.
L05SPPCPMC	1490	L05 Spinous Midpoint: The most projecting point on the spinous process. In case of a large surface area, the midpoint is used.
L05SAPLMMC	1430	Superior Articular Process, Midpint, L05 Left: The midpoint of the left superior articular process of L05.
L05SAPRMMC	1420	Superior Articular Process, Midpoint, L05 Right: The midpoint of the right superior articular process of L05.

TABLE 6.2.6 Number of anatomical pointmarks for subject #23 in LBARFLEX.

BONE	NUMBER OF ANATOMICAL POINTMARKS					
	POSTURE-POSITION CODE					
	10	11	12	13	14	15
L Hip	6	6	6	6	6	6
R Hip	6	6	6	6	6	6
Sacrum	9	9	9	9	9	9
L_5	13	13	13	13	13	13
L_4	13	13	13	13	13	13
L_3	13	13	13	13	13	13
L_2	13	13	13	13	13	13
L_1	13	13	13	13	13	13
T_{12}	13	13	13	13	13	13
T_8	13	13	13	13	13	13
T_4	13	13	13	13	13	13
T_1	13	13	13	13	13	13
C_7	13	13	13	13	13	13
Sternum	-	-	-	-	-	-
R Clavicle	4	4	4	4	4	4
R Scapula	7	7	-	-	7	7
R Humerus	-	-	-	-	-	-

TABLE 6.2.5 Number of anatomical pointmarks for subject #22 in LBARFLEX.

BONE	NUMBER OF ANATOMICAL POINTMARKS							
	POSTURE-POSITION CODE							
	10	11	12	13	14	15	16	17
L Hip	6	6	6	6	6	6	6	6
R Hip	6	6	6	6	6	6	6	-
Sacrum	10	10	10	10	10	10	10	10
L_5	13	13	13	13	13	13	13	13
L_4	13	13	13	13	13	13	13	13
L_3	13	13	13	13	13	13	13	13
L_2	13	13	13	13	13	13	13	13
L_1	13	13	13	13	13	13	13	13
T_{12}	13	13	13	13	13	13	13	13
T_8	13	13	13	13	13	13	13	13
T_4	13	13	13	13	13	13	13	13
T_1	13	13	13	13	13	13	13	13
C_7	13	13	13	13	13	13	13	13
Sternum	4	4	4	4	4	4	4	4
R Clavicle	4	4	4	4	4	4	4	4
R Scapula	7	7	-	-	-	-	-	-
R Humerus	-	-	-	-	-	-	-	-

TABLE 6.2.4 Number of anatomical pointmarks for subject #21 in LBARFLEX.

BONE	NUMBER OF ANATOMICAL POINTMARKS						
	POSTURE-POSITION CODE						
	10	11	12	13	14	15	16
L Hip	5	5	5	5	5	5	5
R Hip	5	5	5	-	5	5	5
Sacrum	8	8	8	13	8	8	8
L_5	13	13	13	13	13	13	13
L_4	13	13	13	13	13	13	13
L_3	13	13	13	13	13	13	13
L_2	13	13	13	13	13	13	13
L_1	13	13	13	13	13	13	13
T_{12}	13	13	13	13	13	13	13
T_8	13	13	13	13	13	13	13
T_4	10	10	10	10	10	10	10
T_1	-	-	-	-	-	-	-
C_7	-	-	-	-	-	-	-
Sternum	4	4	4	4	4	4	4
R Clavicle	-	-	-	-	-	4	4
R Scapula	7	7	7	7	7	7	7
R Humerus	-	-	-	-	-	-	-

TABLE 6.2.3 Number of anatomical pointmarks for subject #23 in LBAREXTN.

BONE	NUMBER OF ANATOMICAL POINTMARKS							
	POSTURE-POSITION CODE							
	00	01	02	03	04	05	06	07
L Hip	6	6	6	6	6	6	6	6
R Hip	6	6	6	6	6	6	6	6
Sacrum	9	9	9	9	9	9	9	9
L_5	13	13	13	13	13	13	13	13
L_4	13	13	13	13	13	13	13	13
L_3	13	13	13	13	13	13	13	13
L_2	13	13	13	13	13	13	13	13
L_1	13	13	13	13	13	13	13	13
T_{12}	13	13	13	13	13	13	13	13
T_8	13	13	13	13	13	13	13	13
T_4	13	13	13	13	13	13	13	13
T_1	13	13	13	13	13	13	13	13
C_7	13	13	13	13	13	13	13	13
Sternum	-	-	-	-	-	-	-	-
R Clavicle	4	4	4	4	4	4	4	4
R Scapula	7	7	7	7	7	7	7	7
R Humerus	-	-	-	-	-	-	-	-

TABLE 6.2.2 Number of anatomical pointmarks for subject #22 in LBAREXTN.

BONE	NUMBER OF ANATOMICAL POINTMARKS							
	POSTURE-POSITION CODE							
	00	01	02	03	04	05	06	07
L Hip	6	6	6	6	6	6	6	6
R Hip	6	6	6	6	6	6	6	6
Sacrum	10	10	10	10	10	10	10	10
L_5	13	13	13	13	13	13	13	13
L_4	13	13	13	13	13	13	13	13
L_3	13	13	13	13	13	13	13	13
L_2	13	13	13	13	13	13	13	13
L_1	13	13	13	13	13	13	13	13
T_{12}	13	13	13	13	13	13	13	13
T_8	13	13	13	13	13	13	13	13
T_4	13	13	13	13	13	13	13	13
T_1	13	13	13	13	13	13	13	13
C_7	13	13	13	13	13	13	13	13
Sternum	4	4	4	4	4	4	4	4
R Clavicle	4	4	4	4	4	4	4	4
R Scapula	7	7	7	7	7	7	7	7
R Humerus	-	-	-	-	-	-	-	-

LUMBAR EXTENSION MOTION SERIES

TABLE 6.2.1 Number of anatomical pointmarks for subject #21 in LBAREXTN.

BONE	NUMBER OF ANATOMICAL POINTMARKS					
	POSTURE-POSITION CODE					
	00	01	02	03	04	05
L Hip	5	5	5	5	5	5
R Hip	5	5	5	5	5	5
Sacrum	8	8	8	8	8	8
L_5	13	13	13	13	13	13
L_4	13	13	13	13	13	13
L_3	13	13	13	13	13	13
L_2	13	13	13	13	13	13
L_1	13	13	13	13	13	13
T_{12}	13	13	13	13	13	13
T_8	13	13	13	13	13	13
T_4	10	10	10	10	10	10
T_1	-	-	-	-	-	-
C_7	-	-	-	-	-	-
Sternum	4	4	4	4	4	4
R Clavicle	-	-	-	4	-	-
R Scapula	7	7	7	7	7	7
R Humerus	-	-	-	-	-	-

6.2 APPENDIX B: NUMBER OF ANATOMICAL POINTMARKS/BONE/POSTURE POSITION/SUBJECT

The following list of tables describes the number of anatomical pointmarks on each bone per subject per posture-position. Tables 6.2.1, 6.2.2, and 6.2.3 describe the data set for the lumbar extension posture positions (LBAREXTN); Tables 6.2.4, 6.2.5, and 6.2.6 describe the lumbar flexion series (LBARFLEX); Tables 6.2.7, 6.2.8, and 6.2.9 describe the abduction motions series (SHABDUCT); and Tables 6.2.10, 6.2.11, and 6.2.12 describe the sidebending series (SIDEBDRT) and two unique experiments (LBARH AND LBARKNEE). Subject 21 was measured to evaluate the effect of different lumbar support heights on spinal posture (LBARH). Subject 23 was measured to evaluate the effect of knee flexion on the seated posture (LBARKNEE). The knees were flexed 145°, 110°, and 80° in the three respective posture-positions (LBARKNEE60-62).

The rows are defined by bone and the numerical code for posture and position define the columns (see tape I, file 1, card 1, field 1, columns 5 and 6 for further definition.). Each cell is defined by a row and column that contains the number of anatomical pointmarks on the bone in a posture and position. If the cell is blank, there are no data. In the tapes no data could be indicated with either a 999.99 or a blank, depending upon the rules given in the description of each file.

RIGHT HUMERUS

POINTMARK ACRONYM	POINTMARK Code	POINTMARK DEFINITION
HUMHEDRMMM	4500	Head of Humerus: The point is at the midpoint of the poximal head on the right humerus.
HUMLETRMSM	4520	Lesser Tubercle: The point is at the superior midpoint of the lesser tubercle on the right humerus.
HUMMEERMMM	4530	Medial Epicondyle: The point is at the anterior-posterior midpoint of the medial epicondyle on the right humerus.
HUMLAERMML	4540	Lateral Epicondyle: The point is the same as above except that it is at the lateral epicondyle on the right humerus.

RIGHT SCAPULA

POINTMARK ACRONYM	Code	POINTMARK DEFINITION
SCAINARMIC	4350	Inferior Angle: The point is at the inferior anterior-posterior midpoint of the inferior angle on the right scapula.
SCASUARMSC	4360	Superior Angle: The point is at the superior anterior-posterior midpoint of the superior angle on the right scapula.
SCAGLFRMML	4340	Glenoid Fossa: The point is at the midpoint of the glenoid fossa on the right scapula.
SCAACPRAMC	4310	Acromion Process: The point is at the most anterior midpoint end of the acromion process on the right scapula.
SCACOPRMML	4330	Coracoid Process: The point is at most lateral anterior-posterior midpoint end of the coracoid process on the right scapula.
SCAACPRMML	4312	Acromion Process Neck: The point is at the lateral anterior-posterior midpoint of the acromion process neck on the right scapula.
SCACOPRAMC	4332	Coracoid Process Neck: The point is at the anterior midpoint of the coracoid process neck on the right scapula.

RIGHT CLAVICLE

POINTMARK ACRONYM	Code	POINTMARK DEFINITION
CLAACJRMML	4120	Acromioclaviclular Joint: The point is at the midpoint of the acromioclaviclular joint surface on the right clavicle.
CLASCJRMMM	4100	Sternoclaviclular Joint: The point is at the midpoint of the sternoclaviclular joint surface on the right clavicle.
CLASHARAMC	4110	Clavicular Shaft Anterior: The point is at the anterior midpoint obtained by extending a line from the midpoint to the midpoint of the acromio-sternoclavicular joint surfaces on the right clavicle.
CLASHARPMC	4111	Clavicular Shaft Posterior: The point is located as above but on the posterior margin of the right clavicle.

STERNUM

POINTMARK ACRONYM	POINTMARK Code	POINTMARK DEFINITION
STESUPCMSC	3930	Suprasternale: The point is at the superior anterior-posterior midpoint on the manubrium of the sternum.
STESCJRMML	3921	Sternoclaviclular Joint, Left: The point is at the anterior- posterior midpoint of the right sternoclaviclular joint surface on the sternum.
STESCJLMML	3920	Sternoclaviclular Joint, Right: Same as above except on the right sternoclaviclular joint surface.
STEBODCAMC	3900	Body of Sternum: The point is at the anterior midpoint found by passing imaginary lines from the 3rd left to 4th right and 3rd right to 4th left costal articulations on the body of the sternum.

in contact, the landmark is taken as the midpoint of the contact area.

HIPILIRASM	1010	Right Iliospinale (ASIS), Summum: The right hip rests on its medial surface with the iliac blade and the pubic symphysis in contact with the horizontal surface of an osteometric board. Move the bone into the right angle corner of the board in such a way that the superior border of the iliac crest is in contact with one of the vertical plates and the anterior border of the iliac crest and the pubic bone are in contact with the second vertical plate of the osteometric board. Illiospinale summum, the anterior superior iliac spine, is defined as the point along the anterior border of the iliac crest in contact with the vertical plate. In cases where a considerable area is in contact, the landmark is taken as the midpoint of the contact area.
HIPSIJRMML	1070	Sacroiliac Midpoint, Right Hip: The point that lies at the intersection of the lines which bisect the superior and inferior poles of the right hip's sacroiliac joint.

HIP

The right hip is used as an example. Insert "L" for the left hip in column 7 of the acronym. The pointmark code changes to 09xx for the left hip.

POINTMARK ACRONYM	Code	POINTMARK DEFINITION
HIPACERMMM	1000	Acetabulion, Center Point, Right Hip: Position the hemisphere within the acetabulum so that the anterior extremity of one of the hemisphere diameter lines is opposite acetabulion anterior. Insert marker through H-point hole, and mark the contact point of the interior surface of the acetabulum.
HIPACERMML	1005	H-Point, Right Hip: Choose a plexiglass hemisphere which best fits the acetabulum of the right hip. Position the hemisphere so that the anterior extremity of one of the perpendicular diameter lines is opposite acetabulion anterior. H-point is the center point of the hemispheric surface.
HIPISCRMIC	1030	Ischiale, Right Hip: The right hip rests on its medial surface with the iliac blade and pubic symphysis in contact with the horizontal surface of an osteometric board. Move the bone into the right angle corner of the board in such a way that the superior border of the iliac crest is in contact with one of the vertical plates, and the anterior border of the iliac crest and the pubic bone are in contact with the second vertical plate of the osteometric board. Ischiale is defined as the highest point on the ischial tuberosity from the surface of the osteometric board.
HIPPUBRAMC	1050	Pubotubercle, Right Hip: This point is found at the anterior most projecting point of the summit of the pubic tubercle when the hip is held in the anatomical position.
HIPILIRPSM	1011	Posterior Superior Iliospinale (PSIS), Right Hip: The right hip rests on its medial surface with the iliac blade and pubic symphysis in contact with the horizontal surface of an osteometric board. Move the bone into the right angle corner of the board in such a way that the superior border of the iliac crest is in contact with one of the vertical plates and the anterior border of the iliac crest and the pubic bone are in contact with the second vertical plate of the osteometric board. Posterior superior iliospinale, the posterior superior iliac spine, is defined as the point along the posterior border of the iliac crest in contact with a moveable vertical plate oriented at right angles to the vertical plates of the osteometric board. In cases where a considerable area is

L05IAPLMMC	1450	Inferior Articular Process, Midpoint, L05 Left: The midpoint of the left inferior articular process of L05.
L05IAPRMMC	1440	Inferior Articular Process, Midpoint, L05 Right: The midpoint of the right inferior articular process of L05.

TABLE 6.2.7 Number of anatomical pointmarks for subject #21 in SHABDUCT.

BONE	NUMBER OF ANATOMICAL POINTMARKS									
	POSTURE-POSITION CODE									
	40	41	42	43	44	45	46	47	48	49
L Hip	5	-	-	-	-	-	-	-	-	-
R Hip	5	-	-	-	-	-	-	-	-	-
Sacrum	8	-	-	-	-	-	-	-	-	-
L_5	13	-	-	-	-	-	-	-	-	-
L_4	13	-	-	-	-	-	-	-	-	-
L_3	13	-	-	-	-	13	13	13	13	13
L_2	13	-	-	-	-	13	13	13	13	13
L_1	13	-	-	-	-	13	13	13	13	13
T_{12}	13	-	-	-	13	13	13	13	13	13
T_8	13	-	13	13	13	13	13	13	13	13
T_4	10	10	10	10	10	10	10	10	10	10
T_1	-	13	13	13	13	13	13	13	13	13
C_7	-	-	-	-	-	-	-	-	-	-
Sternum	4	4	4	4	4	4	4	4	4	4
R Clavicle	-	4	4	4	4	4	4	4	4	4
R Scapula	7	7	7	7	7	7	7	7	7	7
R Humerus	-	4	4	4	4	4	4	4	4	4

TABLE 6.2.8 Number of anatomical pointmarks for subject #22 in SHABDUCT.

BONE	NUMBER OF ANATOMICAL POINTMARKS						
	POSTURE-POSITION CODE						
	40	41	42	43	44	45	46
L Hip	6	-	-	-	-	-	-
R Hip	6	-	-	-	-	-	-
Sacrum	10	-	-	-	-	-	-
L_5	13	-	-	-	-	-	-
L_4	13	-	-	-	-	-	-
L_3	13	-	-	-	-	-	-
L_2	13	-	-	-	-	-	-
L_1	13	-	-	-	-	-	13
T_{12}	13	-	-	-	-	13	13
T_8	13	13	13	13	13	13	13
T_4	13	13	13	13	13	13	13
T_1	13	13	13	13	13	13	13
C_7	13	13	13	13	13	13	13
Sternum	4	4	4	4	4	4	4
R Clavicle	4	4	4	4	4	4	4
R Scapula	7	7	7	7	7	7	7
R Humerus	-	4	4	4	4	4	4

TABLE 6.2.9 Number of anatomical pointmarks for subject #23 in SHABDUCT.

BONE	NUMBER OF ANATOMICAL POINTMARKS							
	POSTURE-POSITION CODE							
	40	41	42	43	44	45	46	47
L Hip	6	-	-	-	-	6	6	-
R Hip	6	-	-	-	-	6	6	6
Sacrum	9	-	-	-	-	-	13	13
L_5	13	-	-	-	-	13	13	13
L_4	13	-	-	-	-	13	13	13
L_3	13	13	-	-	13	13	13	13
L_2	13	13	-	-	13	13	13	13
L_1	13	13	-	13	13	13	13	13
T_{12}	13	13	13	13	13	13	13	13
T_8	13	13	13	13	13	13	13	13
T_4	13	13	13	13	13	13	13	13
T_1	13	13	13	13	13	13	13	13
C_7	13	13	13	-	-	-	13	13
Sternum	-	-	-	-	-	-	-	-
R Clavicle	4	4	4	-	4	4	4	4
R Scapula	7	7	7	7	7	7	7	7
R Humerus	-	4	4	4	4	4	4	4

TABLE 6.2.10 Number of anatomical pointmarks for subject #21 in LBARH (7X).

BONE	NUMBER OF ANATOMICAL POINTMARKS			
	POSTURE-POSITION CODE			
	70	75	76	77
L Hip	5	5	5	5
R Hip	5	5	5	5
Sacrum	8	8	8	8
L_5	13	13	13	13
L_4	13	13	13	13
L_3	13	13	13	13
L_2	13	13	13	13
L_1	13	13	13	13
T_{12}	13	13	13	13
T_8	13	13	13	13
T_4	10	10	10	10
T_1	-	-	-	-
C_7	-	-	-	-
Sternum	4	4	4	4
R Clavicle	-	4	4	-
R Scapula	7	7	7	7
R Humerus	-	-	-	-

TABLE 6.2.11 Number of anatomical pointmarks for subject #22 in SIDEBDRT (2X).

BONE	NUMBER OF ANATOMICAL POINTMARKS	
	POSTURE-POSITION CODE	
	20	22
L Hip	6	6
R Hip	6	-
Sacrum	10	-
L_5	13	13
L_4	13	13
L_3	13	13
L_2	13	13
L_1	13	13
T_{12}	13	13
T_8	13	-
T_4	13	-
T_1	13	-
C_7	13	-
Sternum	4	-
R Clavicle	4	-
R Scapula	7	-
R Humerus	-	-

TABLE 6.2.12 Number of anatomical pointmarks for subject #23 in SIDEBDRT (2X) and LBARKNEE (6X).

BONE	NUMBER OF ANATOMICAL POINTMARKS				
	POSTURE-POSITION CODE				
	20	22	60	61	62
L Hip	6	-	6	6	6
R Hip	6	-	6	6	6
Sacrum	9	-	9	9	9
L_5	13	13	13	13	13
L_4	13	13	13	13	13
L_3	13	13	13	13	13
L_2	13	13	13	13	13
L_1	13	13	13	13	13
T_{12}	13	13	13	13	13
T_8	13	13	13	13	13
T_4	13	-	13	13	13
T_1	13	-	13	13	13
C_7	13	-	13	13	13
Sternum	-	-	-	-	-
R Clavicle	4	-	4	4	4
R Scapula	7	-	7	7	7
R Humerus	-	-	-	-	-

6.3 APPENDIX C: ANATOMICAL POINTMARKS USED IN DEFINING ANATOMICAL REFERENCE FRAMES.

The following table describes the anatomical axis system used in tape II, file 5 to investigate relative motions between links in the skeletal system. The list is organized by bone and the example for the vertebrae is to be used for all vertebrae. The table gives the anatomical pointmark acronmym (See Appendix A), the direction of the axis passing through that point, and beneath the entry is the numerical code that can be used in tape I, files 1 and 3 to obtain the cartesian coordinates in either the SRP or anatomical frame of reference.

The first 2 digits of the bone structure code given below the anatomical pointmark name in the vertebrae can range from 13 to 38 depending upon the vertebrae. See the code given in the documentation for file 1, card 1, columns 7-8.

TABLE 6.3.1 Anatomical Pointmarks for Each Anatomical Reference Frame

BONE	ANATOMICAL POINTMARKS		
LEFT HIP	HIPILILPSM (-x),	HIPILILASM (+x),	HIPISCLMIC (-z)
	0911	0910	0930
RIGHT HIP	HIPILIRPSM (-x),	HIPILIRASM (+x),	HIPISCRMIC (-z)
	1011	1010	1030
SACRUM	SACBD1LMSL (+y),	SACBD1RMSL (-y),	SACBD1CASC (+x)
	1103	1102	1100
STERNUM	STESCJLMML (+y),	STESCJRMML (-y),	STEBODCAMC (-z)
	3920	3921	3900
CLAVICLE	CLAACJRMML (+y),	CLASCJRMMM (-y),	CLASHARPMC (-x)
	4120	4100	4111
SCAPULA	SCAGLFRMML (+y),	SCASUARMSC (-y),	SCAINARMIC (-z)
	4340	4360	4350
HUMERUS	HUMLAERMML (+y),	HUMMEERMMM (-y),	HUMHEDRMMM (+z)
	4540	4530	4500
VERTEBRAE	L05BODLMIL (+y),	L05BODRMIL (-y),	L05BODCAIC (+x)
	1404	1406	1405

6.4 APPENDIX D: Calculation of Relative Rotations and Translations.

The translations of the moving body are calculated by a vector subtraction of the first and second positions of the origin of the moving body.

The following discussion of the rotations is based primarily upon the work of Suh and Radcliffe (1983) with modifications to fit the application in Systems Anthropometry Laboratory.

If we adopt a sequence of three rotations around a certain x, y, z axis system,

(1) α about the z-axis

(2) β about the y-axis

(3) γ about the x-axis

the final position of the vector V_2 can be described by

$$V_2 = [R_{\delta,x}]\,[R_{\beta,y}]\,[R_{\alpha,z}]\,V_1$$

where V_1 is the initial position of the vector, and $[R_{\alpha,z}]$ represents rotation of α around z.

We can also write,

$$V_2 = [R_{\alpha\beta\gamma}]\,V_1$$

and $\left[R_{\alpha\beta\gamma}\right] = [R_{\gamma,x}]\,[R_{\beta,y}]\,[R_{\alpha,z}]$

$$= \begin{bmatrix} \cos\alpha\cos\beta & -\sin\alpha\cos\beta & \sin\beta \\ \sin\alpha\cos\gamma + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & -\cos\beta\sin\gamma \\ \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma & \cos\alpha\sin\gamma + \sin\alpha\sin\beta\cos\gamma & \cos\beta\cos\gamma \end{bmatrix}$$

If we know the rotation matrix

$$\left[R_{\alpha\beta\gamma}\right] = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

Then, the 3 rotation angles can be solved.

$$\cot \alpha = -\frac{a_{11}}{a_{12}}$$

$$\sin \beta = a_{13} \tag{1}$$

$$\tan \gamma = -\frac{a_{22}}{a_{33}}$$

Consider two bones as shown in Figure 6.4.1

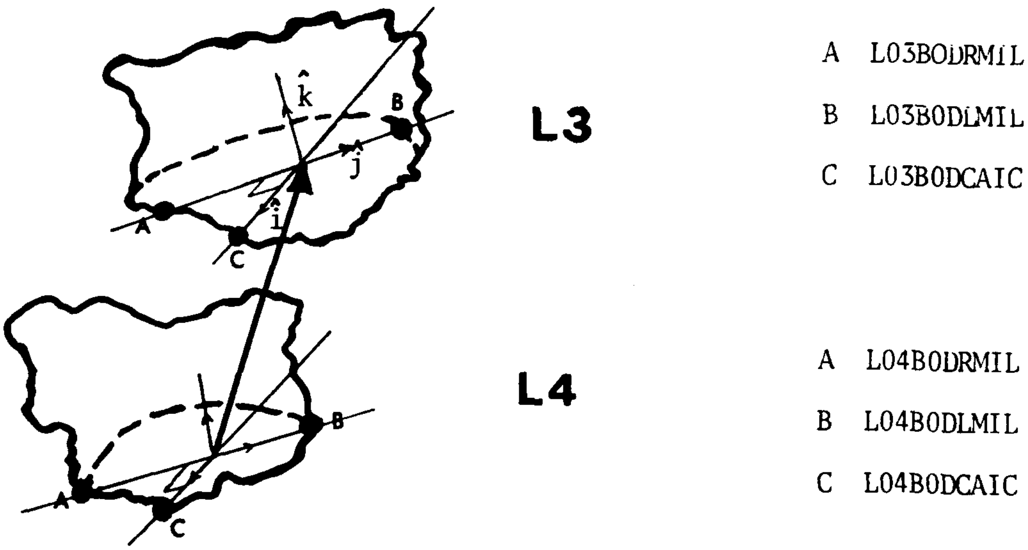


Figure 6.4.1 Relative motion of two bones.

The data used in this calculation are six anatomical pointmarks on the anatomically superior bone and the anatomically inferior bone. Namely, L03BODLMIL, L03BODRMIL, L03BODCAIC AND L04BODLMIL, L04BODRMIL, L04BODCAIC.

1) Data of these six anatomical POINTMARKS are given in the SRP frame, for the 00 and 05 positions of the LBAREXTN (lumbar extension) motion series, for example. (These are the results obtained from the three-dimensional data analysis, as detailed in section 6.2 of the AFAMRL-TR-83-016 Final Report.)

2) All data are transformed to the anatomical frame of the inferior bone, i.e. L04.

3) The origin of the superior bone, L03, is calculated for the two positions, i.e. LBAREXTN00 and LBAREXTN05. This describes the translation of the above bone as seen from the anatomical bone frame of the inferior bone.

4) The three rotation angles as given by equation (1) are calculated by assuming the rotation sequence to be: first, around the $\hat{j}$ axis, and secondly, around the $\hat{k}$ axis, and thirdly, around the $\hat{i}$ axis. (The $\hat{i}$, $\hat{j}$, $\hat{k}$ axis are shown in Figure 6.4.1.) Since the arbitary axis system used in deriving equation (1) is different from the chosen rotation sequence, the data undergo a temporary transformation but α, β, γ shown in the result section is around $\hat{j}$, $\hat{k}$, $\hat{i}$ respectively. Thus, for the LBAREXTN motion series, the primary axis of roation is $\hat{j}$; the secondary axis of rotation is $\hat{k}$; and the tertiary axis of rotation is $\hat{i}$. The rotation sequence chosen above holds true for both the LBAREXTN and the LBARFLEX positions. This is because the $\hat{j}$ is expected to be where the primary axis of rotation of the vertebrae is, and some rotation around $\hat{k}$ also.

However, for SHABDUCTN and SIDEBDRT positions, the primary axis of rotation is expected to be along the $\hat{i}$ axis, the secondary axis of rotation is expected to be along the $\hat{k}$ axis. Thus the α, β, γ angles shown in the result section are around $\hat{i}$, $\hat{k}$, $\hat{j}$ respectively.

7.0 List of References.

1. Reynolds, H. M. and Leung, S-C. 1983 "A Foundation for Systems Anthropometry: Lumbar/Pelvic Kinematics." Air Force Aerospace Medical Research Laboratory, AFAMRL-TR-83-016. Wright-Patterson Air Force Base, Ohio.

2. Reynolds, H. M., Hallgren, R., and Marcus, J. 1982 "Systems Anthropometry: Development of a Stereoradiographic Measurement System." J. Biomechanics 15(4):229-233.

3. Suh, C. H. and Radcliffe, C. W. 1983 Kinematics and Mechanism Design. Robert E. Krieger Publ. Co., Malabar, Florida.

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